

# Analysis of reflected Global Positioning System (GPS) signals from land for soil moisture determination and topography mapping

Omar Torres\*<sup>a</sup>, Stephen J. Katzberg\*\*<sup>b</sup>

<sup>a</sup>The University of Texas at El Paso/Langley Research Center

<sup>b</sup>Langley Research Center, Hampton Virginia, 23681

## ABSTRACT

GPS signals reflected from the ocean surface have been used in remote sensing applications to determine sea-state and wind speed. Studies show that, with rougher surfaces, GPS signal pulses scatter more, which creates weaker and wider pulses at the receiver. Based on this model, the correlation between soil moisture, topography, and GPS signals was studied using reflections off the ground. The data used for the study were gathered during two flights in 1998 and 2001 around Austin, Texas and Albuquerque, New Mexico and later processed at Langley Research Center. The power of the signals were analyzed and plotted over Digital Elevation Models (DEMs) and Landsat7 images (near- and mid-infrared bands) to interpret the correlation of signal behavior with topography. In addition, the received signal's conduct was correlated with soil moisture data obtained from the Department of Agriculture's Soil Climate Analysis Network (SCAN) sites at Prairie View (Texas) and Adams Ranch (New Mexico). The strengths of the reflected signals were observed larger near known bodies of water and farmlands where soil moisture levels are known to be high. In general, for flat lands, the power of the signals and soil moisture contents appeared to have a close-to-linear relationship. In addition, the received pulses widened when reflected over rapid-changing topography in Texas, but any relationship among these was not perceived in New Mexico. Further studies are needed to obtain a definite relationship among soil moisture and reflected signal strength and to introduce satellite position in the signal-topography study.

Keywords: GPS, soil moisture, topography.

## 1. INTRODUCTION

It is well known that L-band GPS signals can travel through fog or clouds without any significant change. However, these same signals will reflect from a denser layer of water, such as the ocean surface or soil moisture. Sometimes these reflections can be strong enough to interfere with the GPS signals incoming directly from the satellite constellation. Utilizing these findings, it has been proposed to use these reflections for remote sensing purposes<sup>2</sup>. However, while these signals have been well documented over the sea surface, there is poor knowledge about these reflections over land. This study proposes to exploit the ground penetration capabilities of the L-band signals from the GPS constellation to map the terrain below the receiver as well as to identify the amount of soil moisture in the reflection area.

In order to determine a correlation between the amount of soil moisture, topography and the reflected signals, two different features were studied, first the amplitude of the signal, and, second, the widening of the received pulse. By being able to determine the soil moisture content and the topography using only reflected GPS signals, several fields could benefit. First, agriculture: there are only a few stations around the country that measure soil moisture, which can lead to wrong estimates over wide areas. Determining soil moisture using GPS signals would allow the determination of it with a much greater accuracy, thus helping in the decisions for agricultural distribution over any part of the world. Two, using these same reflections, a much more accurate and cheaper altimeter may be applied. Since current systems in use tell the altitude of an aircraft from the center of the Earth, and referencing on the WGS-84 ellipsoid, the estimate may contain errors, which can vary between 75m and 135m (in height). Using GPS reflections, the altitude can be estimated from local surface, yielding readings that are accurate within a few meters. Three, using reflection strength and scattering can be a way to determine topography in real time without having to have a transmitter onboard the transport being used. From this side of the house, Geology, as well as military, may be benefited.

---

\*email: otorres2@utep.edu;

\*\*email: s.j.katzberg@larc.nasa.gov; phone: (757) 864-1970;

## 2. BACKGROUND

In 1994 French engineers reported an accidental acquisition of GPS signals reflected over the ocean, which in turn directed them towards false positioning information<sup>1</sup>. The potential of these reflected signals was later discovered at the National Aeronautics and Space Administration's (NASA's) Langley Research Center, where they were applied for oceanographic and ionospheric remote sensing. It was later discovered that a calm sea surface acts as a mirror for GPS signals, reflecting pulses that may be nearly as strong as the incoming rays. However, the roughness on the surface will scatter the incoming beam, creating a loss of power and/or a widening of the correlation function in the received signal. This behavior can be later correlated with the roughness of the sea surface, thus being able to determine the sea state and, most importantly, the wind-speed at the surface.

The GPS satellite constellation orbits the Earth at an altitude of over 20,000 km over the surface of the Earth<sup>3</sup>. Because of the distance, the transmitted wave will behave as an incoming plane-wave close to the surface. Part of the plane-wave can be read with a Right-Hand-Circularly Polarized (RHCP) zenith-oriented antenna on top of an airplane to perform common measurements of positioning. However, part of the same plane-wave may hit a dense layer of water (sea or soil moisture) at an angle  $\gamma$  and bounce back to space at that same angle (Figure 1) reaching some platform carrying the receiver, such as an airplane, at a later time (represented by the time delay  $\delta$ )<sup>2</sup>. Over a calm ocean, the power of the reflected signal has been measured at over 60 percent of the original wave power and, although weaker, reflections inland may reach up to 55 percent. However, obeying boundary conditions, the reflected signals change polarity when reflecting: these signals are discarded from the RHCP antenna but can be read with a Left-Hand-Circularly Polarized (LHCP) antenna oriented towards nadir.

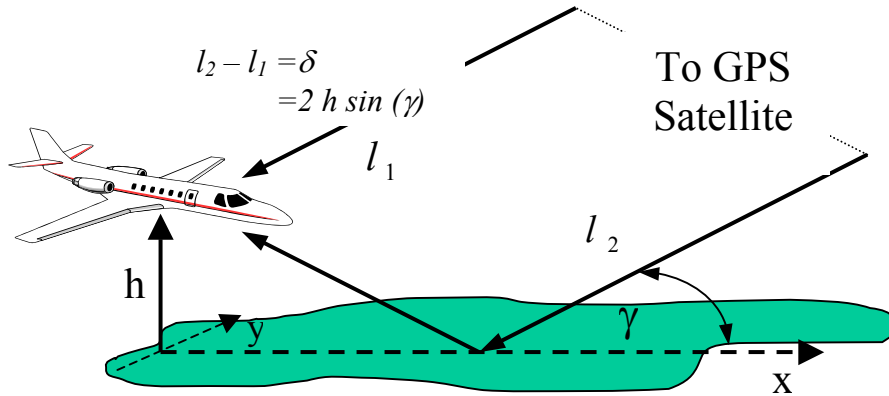


Figure 1. Illustration of geometry describing reflected GPS signals in an aeronautical application. The GPS satellites are assumed to provide uniform signals in the form of a plane wave.

Ideally, the reflected signals will echo from a perfectly planar surface and the reflection will be purely specular<sup>2</sup>. However, in reality reflections take place in non-perfectly planar surfaces. The GPS signals may be received at the LHCP antenna from different bouncing angles (dictated by the roughness of the reflecting surface). At the antenna, the signal power redirected by a rough surface decreases significantly as the reflection point moves away from the nominal specular point<sup>1</sup>. The scattering effect from a rough surface will be manifested at the receiver as reflecting signals from an elliptical area around the specular point described as the “glistening surface” (for a more detailed explanation, please refer to reference 2). The *lambda* function (Figure 2a), which describes the autocorrelation properties of the GPS signal, accumulates power from the glistening surface<sup>2</sup>. Over numerous experiments over the ocean, it has been shown that at different surface roughness the received lambda function (or pulse) will widen and/or lose power. The integral of this pulse over delayed time yields information about sea-state and wind speeds at the ocean surface. Figure 2b shows different correlation functions of reflected GPS signals from the Pacific Ocean near the coasts of Oregon

At the ocean, the reflected signal will be strongest with a calm sea surface. However, the reflecting surface will morph constantly with waves, ripples, etc. creating constant change in the received pulses. On the other hand, inland surface change over time is insignificant, but water content (mainly in the form of soil moisture) varies over large areas modifying the strength of the reflected signal. Having GPS reflected signals from the ocean as a reference, the change in strength of the reflected signal inland may be used to determine water content (soil moisture) at the reflection area.

Furthermore, the time response of the reflections can be studied to determine the pattern followed by moisture under busy topography in an attempt to predict surface behavior.

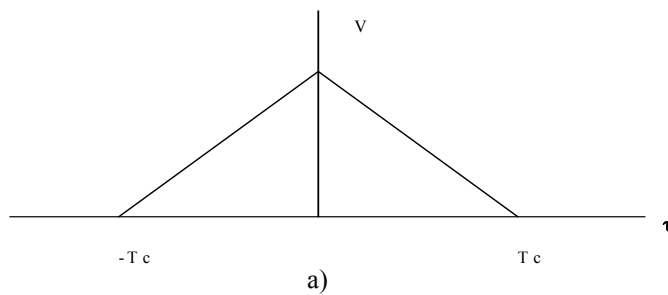
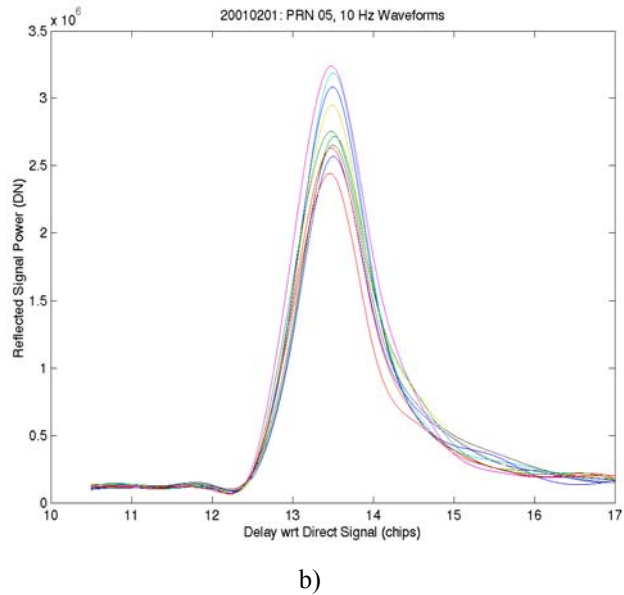


Figure 2. a) The ideal lambda function that describes the autocorrelation properties of the GPS signals.  
b) Actual measurements of the lambda function over the coasts of Oregon.



### 3. APPROACH

Data sets used were obtained during two different flights: a NASA flight over New Mexico, near Albuquerque, during August 6 1998, and a NOAA flight over Austin Texas, during January 18 2001. The data was collected and later processed at NASA's Langley Research Center using ArcView GIS software by the Environmental Systems Research Institute, Inc. (ESRI) and other tools. In addition, topography-signal correlation was done with DEMs and Landsat7 images of the areas mentioned above.

The specular point of reflection takes place at a point slightly off from the receiver's position, described in Equations 1a and 1b. Although there may be more than one reflecting point over rough areas, the Earth's surface was assumed flat when computing the specular point of reflection. Under different circumstances, this assumption may be replaced by more accurate data such as DEM figures; nonetheless, the results presented in this paper will not change considerably by this assumption.

$$\Delta lat = \frac{h \cdot \cot(\gamma) \cdot \cos(\phi)}{Re} \quad (1a)$$

$$\Delta long = \frac{h \cdot \cot(\gamma) \cdot \sin(\phi)}{Re \cdot \cos(\theta)} \quad (1b)$$

$\gamma$  is the vertical angle with respect to the surface plane (angle of reflection) on which the reflections take place. The position angle of the satellite from north is represented by  $\phi$  (azimuth angle), and  $Re$  is the radius of the Earth. To reduce positioning error on the overlay of the maps and the reflection data, the radius of the Earth was computed using Equation 2, which expresses the surface of the Earth as an ellipsoid of revolution; the ellipsoid used here is called World Geodetic Datum 1984 (WGS-84) ellipsoid.

$$Re^2 = \frac{b^2}{1 + \frac{b^2}{a^2} \cdot \sin^2 \theta} \quad (2)$$

where  $a = 6378137$  is the semi-major axis of the ellipsoid describing the earth,  $b = 6356752.3142$  is the semi-minor axis, and  $\theta$  is the angle from the Equator on the surface of the Earth (latitude) where the distance from the center of the Earth must be computed. The desired latitude was obtained from the airplane's navigation system.

Moreover, it is known that water absorbs energy in the infrared band and that it appears black when observed under such wavelength. Landsat7 images in the near- and mid-infrared bands were used as a background for the plotting of the reflected signals. These images offered best contrast between known bodies of water and land. In addition, for better understanding of the signal behavior away from water, the soil moisture closest to the area of interest was gathered from the United States Department of Agriculture (USDA). Data were obtained from two SCAN sites in Prairie View, Texas, and Adam's Ranch, New Mexico for the time of the flights. The data obtained were in the form of percentage of water per volume of soil and were assumed constant through the area of interest.

For the soil moisture study, the strength of the reflections was analyzed over flat lands to avoid pulse scattering over wide areas. These flat lands were selected by observing a slower rate of change of the surface's elevation using the contour capability of ArcView and DEMs. In contrast, the correlation of signal behavior and topography was contemplated over areas where the surface was rougher, or rapid changes of altitude took place. These two areas of study are not necessarily exclusive.

## 4. RESULTS

### 4.1 Soil Moisture

The relative signal strength was plotted over a Landsat7 image in the mid-infrared band. Although with an offset, a correlation between rivers and the strength of the signals was observed. Figure 3 shows two regions of a Landsat7 image with the reflected signals shown with dots, bigger dots represent stronger signals, which took place near obvious high soil moisture areas. In this case, the receiver was moving in a right-left pattern causing part of the observable offset on the plotting of the signals. However, it is thought that an error of the GPS system when calculating the exact height of the airplane and the assumption of the flatness of the surface produced the observable offset for the specular points.

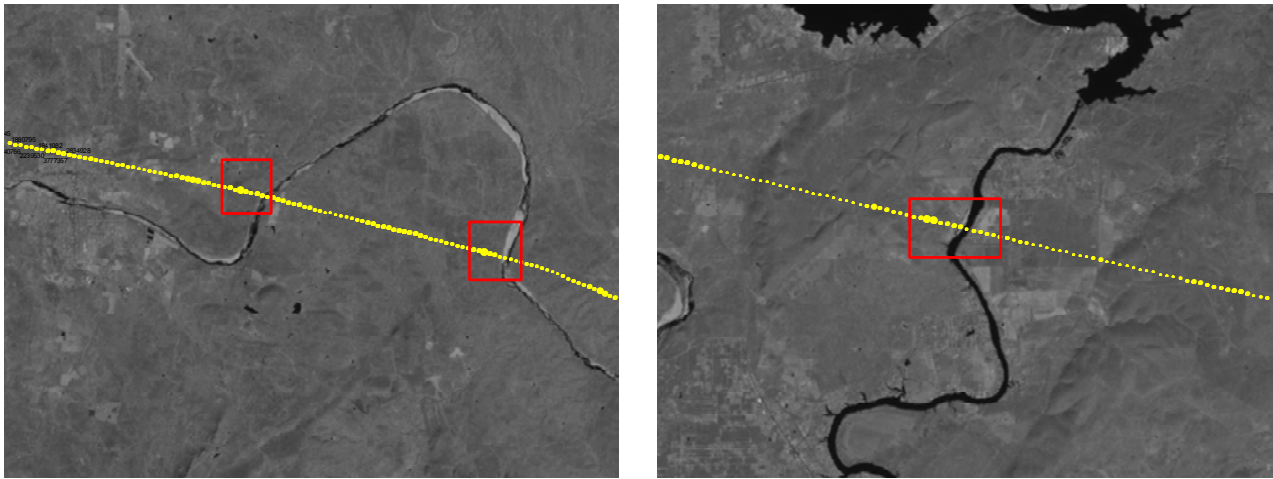


Figure 3. Stronger signals were observed near known bodies of water

In addition, signal reflections in an agricultural area were observed large in power for the most part, which indicated a high level of soil moisture. These strong reflections were later correlated with the SCAN site's readings. Soil moisture data for that area showed that the amount of water per volume of soil was on the average of 34.02%, which is a high value (typical value for land under cultivation). The magnitude of the maximum reflected signal at this area was noted to be approximately 1160445.29 units (Figure 4a).

Soil moisture in New Mexico during the time of the flight was observed low relative to soil moisture percentage in Texas, 11.09% per soil volume on the average (Figure 4b). The maximum signal received from this area was noted to be

approximately 346679.69. By taking the ratio of reflected signal strength to soil moisture percentage for both data sets, it was noticed that both ratios yielded similar results. It is thought that these results point towards a possible linear relationship between the amount of soil moisture present and the strength of the reflected signal.

Texas:  
Avg. Soil Moisture = 34.02%  
Maximum Strength = 1160445.29

$$\frac{\text{Signal Strength}}{\text{Soil Moisture}} \cong 34110.38$$

New Mexico:  
Avg. Soil moisture = 11.09%  
Maximum Strength = 346679.69

$$\frac{\text{Signal Strength}}{\text{Soil Moisture}} \cong 31260.57$$

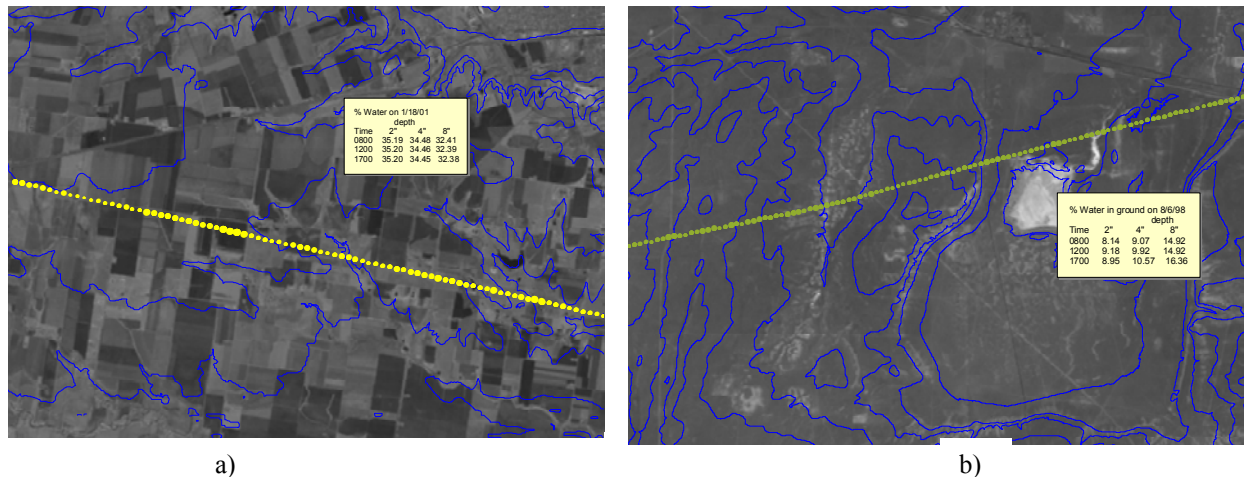


Figure 4. Soil Moisture was studied where elevation change was at lower rate. Satellites in view were GPS-2 in a) Texas, and GPS-17 in b) New Mexico

4.2 Topography

As with soil moisture, the topography was observed using reflected signal strength, however the extra feature of pulse broadening was introduced into the study. Figure 5 shows pulse broadening in red triangles (bigger triangles mean broader functions) over a busy topography region. A widening was noted in the correlation function where elevation changed rapidly in Texas. In addition, at the places where the pulse was wider, the power received was much lower noting an inverse relationship between signal strength and broadening. The satellite in view was GPS-2 with an average elevation angle of 39 degrees and an azimuth angle of approximately 303 degrees, northeast of the flight path.

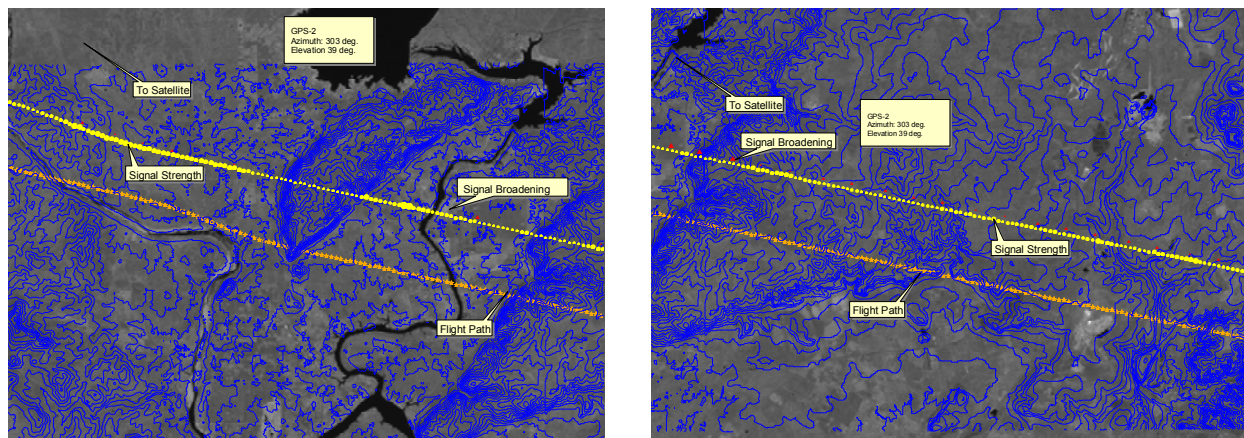


Figure 5. Inverse relationship between the broadening of the correlation function and the strength of the signal in Texas.



In New Mexico, three satellites were in view at the time of the flight, GPS-6, GPS-17, and GPS-30, however, the broadening of the pulses for these satellites were not available at the time of the study. Despite that, an opposite signal strength behavior was observed in New Mexico as compared to Texas (Figure 6): signal strength over busy topography was observed larger. The position of the satellite relative to the flight path was different from the one in Texas.

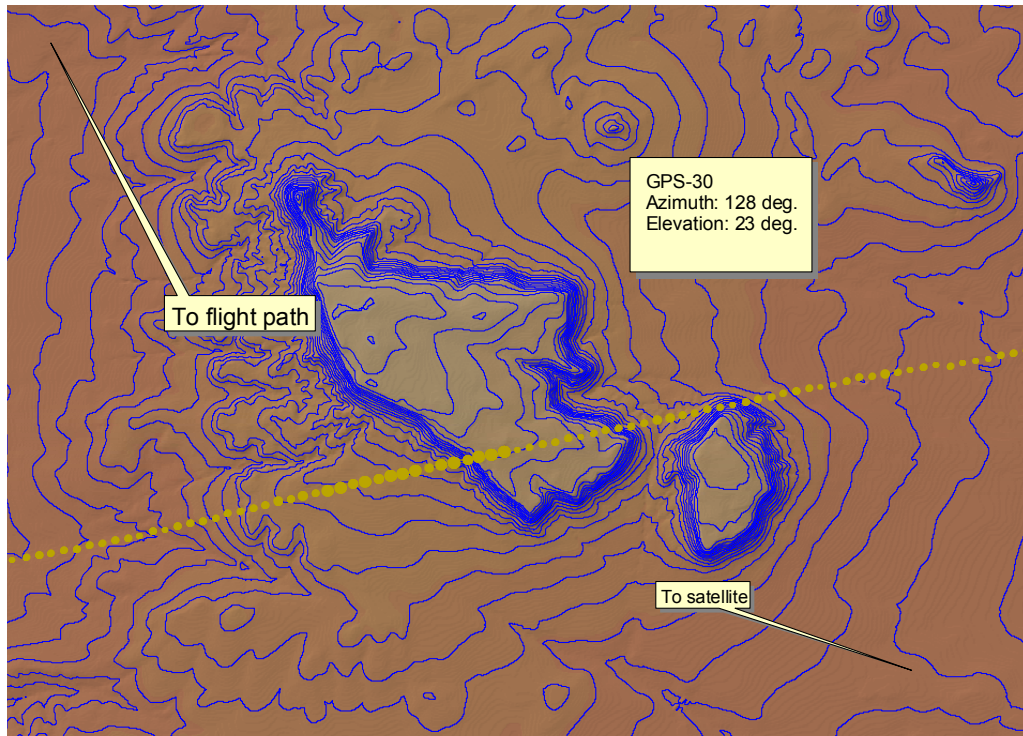


Figure 6. The transmitter-receiver position during the data collection process in New Mexico showed that topography plays a major role on signal strength at the receiver.

## 5. CONCLUSIONS

Signal strength appears to follow a linear pattern (over flat surfaces) proportional to the amount of soil moisture below the receiver. However, signal behavior for rough surfaces varies unpredictably. Although at the time of data collection in New Mexico the soil moisture was extremely low, strong reflections were observed in the area. These results show that even over dry areas, there is enough soil moisture close to the surface to reflect GPS signals, which may lead to a soil moisture determination.

As expected, the normal vector of the reflecting surface played a major role in the reception on the signal over rough surfaces. The surface of reflection acts as a mirror, reflecting most of the energy in the direction dictated by the surface normal, which leads to a stronger or weaker signal depending on the transmitter-receiver position.

A connection between signal behavior and surface change could not be established during the relatively short period of the study. More reflection data are needed at places of known soil moisture content for correlation with signal behavior. Furthermore, more studies are needed to correlate signal behavior with topography for different combinations of elevation change and transmitter-receiver positions.

## 6. REFERENCES

1. A. Komjathy, J. L. Garrison, V. U. Zavoronty, "GPS: A New Tool for Ocean Science." *GPS WORLD*, April 1999.
2. S. J. Katzberg, J. L. Garrison, "Utilizing GPS to Determine Ionospheric Delay Over the Ocean." *NASA Technical Memorandum 4750*, 1996.
3. B. W. Parkinson, J. J. Spilker Jr., *Global Positioning System: Theory and Applications Volume I*, pp 29-55, American Institute of Aeronautics and Astronautics, Inc., Washington, 1995.
4. G. B. Thomas, *Calculus and Analytic Geometry*. Addison-Wesley, London, 1961.